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THE REMOVAL OF DF (V = 3 AND 4) BY H AND D ATOMS. (U)

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The Removal of DF ($v = 3$ and 4) by H and D Atoms

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12 April 1982

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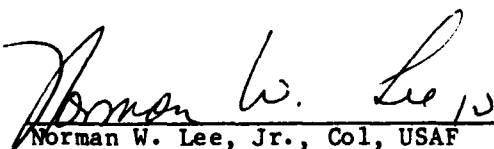
This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.


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This is in excellent agreement with a previous measurement of the $F + HD$ rate coefficient obtained by Berry.

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I. INTRODUCTION

The deactivation of vibrationally excited DF by the products of the $F + D_2$ reaction directly affects the performance of the DF chemical laser. Discussions of the various deactivation processes and their recommended rate coefficients can be found in Refs. 1-3. In the cold-reaction DF laser, one D atom is produced for each DF molecule, and the effects of DF(v) deactivation by D atoms must be considered. The analogous case of HF(v) deactivation by H atoms has been studied in several laboratories.⁴⁻⁸ Of particular importance is the observation⁶⁻⁸ that the removal rates of HF(v) by H increase very dramatically for $v \geq 3$.

The only measured rates of DF(v) deactivation by H and D atoms to be reported⁵ to date are for $v = 1$. In the present study we have measured the removal rates of DF($v = 3$ and 4) by H and D atoms at 295 K. The experiments were performed in the same apparatus as the previous HF(v) -H experiments^{6,7} using the technique of laser-induced fluorescence. Helium, D_2 , and a small amount of DF flow through a fluorescence cell in which a pulsed DF laser pumps a small fraction of the DF($v = 0$) to $v = 3$ and 4 by sequential photon absorption. Before reaching the cell the helium and D_2 flow through a microwave discharge which produces D atoms. The difference in the decay rates of the DF overtone fluorescence obtained with and without D atoms is used to determine the deactivation coefficients.

The removal of DF($v = 4$) by D atoms can proceed by three channels:



These channels, nonreactive deactivation (1), reactive deactivation by D-atom exchange (2), and the back reaction of the $F + D_2$ reaction (3), are discussed in Section IV.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were performed in the fluorescence cell-flow system described in Ref. 6 and shown schematically in Fig. 1. The photomultiplier was positioned at the end of the flow tube so that fluorescence from the entire length of the cell would contribute to the signal. Because of the low signals for DF($v = 3, 4$), it was not possible to place the photomultiplier transverse to the laser beam. The required position of the photomultiplier precluded direct measurements of the H(D) atom concentrations with the catalytic probe used in Ref. 6. Therefore, the density of the H and D atoms was inferred from their effect on the decay time of the HF(3) fluorescence and the previously measured removal rate coefficients.⁷ Experiments were performed in which the HF impurity in the DF was pumped to the $v = 3$ level with an HF laser. The subsequent decay rate of HF($v = 3$) was measured with and without the atoms present.

An RCA GaAs photomultiplier was used to monitor the fluorescence from HF($v = 3$) and DF($v = 4$). A Kodak Wratten filter (87B) and a 0.62-cm sheet of Plexiglas were used to attenuate scattered light from the microwave discharge and the laser pulse. A DuMont Type 6911 (S-1 response) photomultiplier behind a Corning CS7-56 filter and 0.62 cm of Plexiglas was used to monitor DF($v = 3$). Typically, 256 or 512 pulses were averaged for DF($v = 3$) and DF($v = 4$), whereas only 32 to 64 were required for HF($v = 3$). Other apparatus, such as the DF-pulsed laser and the signal processing instruments, have been previously described.⁹

The experiments were performed at room temperature (295 K) and at a total pressure of 5.5 Torr. The bulk of the gas flow was helium with partial pressures of ~ 0.02 Torr DF, ~ 0.04 Torr $D_2(H_2)$, and ~ 0.02 Torr D(H) atoms.

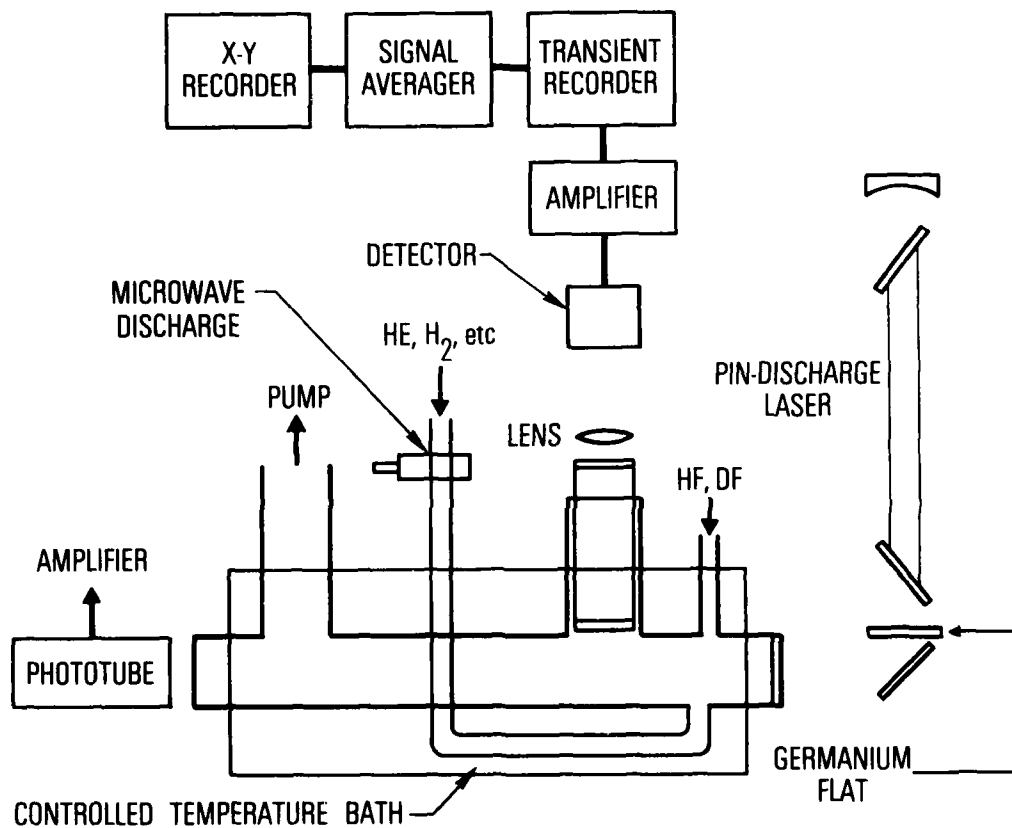


Fig. 1. Schematic of Apparatus

III. RESULTS

A. VIBRATIONAL RELAXATION OF DF(v = 3) BY D ATOMS

The DF 3 → 0 overtone fluorescence was recorded with and without the D atoms produced by the microwave discharge. The fluorescence decay times were ~ 25% shorter with the D atoms present. As described in Ref. 6,

$$\Delta\left(\frac{1}{\tau}\right) = \tau_{\text{on}}^{-1} - \tau_{\text{off}}^{-1} = (k_{\text{DF-D}} - \frac{1}{2} k_{\text{DF-D}_2})[\text{D}] \quad (4)$$

The exponential decay times of the fluorescence traces and the calculated values of $\Delta(1/\tau)$ are presented in Table 1. The latter have an average value of $6 \times 10^{-3} \mu\text{s}^{-1}$ if all five values are included, or $5.3 \times 10^{-3} \mu\text{s}^{-1}$ if the high and low values are excluded. This compares to a value of $6.3 \times 10^{-2} \mu\text{s}^{-1}$ obtained under the same conditions for HF(v = 3) removal by D atoms. Using the previously measured value⁷ of $5.9 \times 10^{13} \text{ cm}^3/\text{mol-s}$ for the HF(3)-D removal rate, we estimate $5 \pm 2 \times 10^{12} \text{ cm}^3/\text{mol-s}$ for the value of $k_{\text{DF-D}} - 1/2 k_{\text{DF-D}_2}$. The value⁹ of $k_{\text{DF-D}_2} = 2.8 \times 10^{11} \text{ cm}^3/\text{mol-s}$ is small compared to the uncertainty in the measurement and can be neglected.

B. VIBRATIONAL RELAXATION OF DF(v = 3) BY H ATOMS

The H atoms had a smaller effect on the DF(v = 3) fluorescence decay times than the D atoms. The values of $\Delta(1/\tau)$ for DF(v = 3) are smaller by a factor of about 35 than the values for HF(v = 3) (see Table 2). Using a value of 6.3×10^{13} for the HF(v = 3)-H removal rate,⁶ we obtain a value of about $2 \times 10^{12} \text{ cm}^3/\text{mol-s}$ for $(k_{\text{DF-H}} - 1/2 k_{\text{DF-H}_2})$. The small value⁹ of $0.8 \times 10^{11} \text{ cm}^3/\text{mol-s}$ for $k_{\text{DF-H}_2}$ makes it a negligible contribution. Since the decay times with and without the atoms differ only by about 10%, there is a large uncertainty in the measured value of $k_{\text{DF-H}} = 2 \pm 2 \times 10^{12} \text{ cm}^3/\text{mol-s}$.

C. VIBRATIONAL RELAXATION OF DF(v = 4) BY D ATOMS

The data for DF(v = 4) removal by D atoms are listed in Table 3. The exponential decay times of the fluorescence traces obtained with and without the D atoms differ by about a factor of 2. The decay rates for HF(v = 3) are

Table 1. Removal Rates of DF(v = 3) by D Atoms

Run	$\tau_{\text{on}},$ μs	$\tau_{\text{off}},$ μs	$\Delta(1/\tau) \times 10^3,$ μs^{-1}	$\Delta(1/\tau)$ for HF(v = 3), μs^{-1}
1	44	97	12.4	} $(5.5 \pm 1) \times 10^{-2}$
2	51.6	69.5	5.0	
3	54.4	78	5.6	
4	59	66	1.8	
5	54	75.1	5.2	
			6 ± 2	

Table 2. Removal Rates of DF(v = 3) by H Atoms

Run	$\tau_{\text{on}},$ μs	$\tau_{\text{off}},$ μs	$\Delta(1/\tau) \times 10^3,$ μs^{-1}	$\Delta(1/\tau)$ for HF(v = 3), μs^{-1}
1	73.1	66.6	-1.4	} $(5.0 \pm 1) \times 10^{-2}$
2	52.2	56.2	1.3	
3	45.7	49.1	1.5	
4	49.5	56	2.3	} $(8.0 \pm 1) \times 10^{-2}$

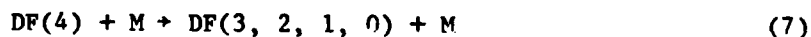
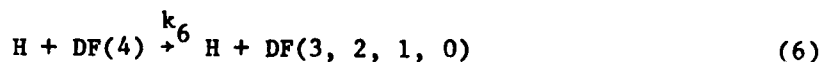
Table 3. Removal Rates of DF(v = 4) by D Atoms

Run	$\tau_{\text{on}},$ μs	$\tau_{\text{off}},$ μs	$\Delta(1/\tau) \times 10^2,$ μs^{-1}	$\Delta(1/\tau)$ for HF(v = 3), μs^{-1}
1	40.4	95	1.43	$(3.0 \pm 0.5) \times 10^{-2}$
2	36.5	85	1.56	
3	40.9	82	1.23	
4	43	92	1.23	
5	36.1	100	1.77	$(4.1 \pm 0.5) \times 10^{-2}$
6	33.9	100	1.95	
7	29.9	98	2.34	$(4.7 \pm 0.5) \times 10^{-2}$
8	29.9	98	2.34	
9	34.2	118	2.23	$(5.4 \pm 0.5) \times 10^{-2}$
10	40	125	1.70	$(5.0 \pm 0.5) \times 10^{-2}$
11	33.8	130	2.19	$(4.6 \pm 0.5) \times 10^{-2}$

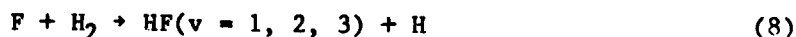
plotted versus those of DF(v = 4) in Fig. 2. The value of $\Delta(1/\tau)$ for DF(v = 4) averaged 0.46 times the values of $\Delta(1/\tau)$ for HF(v = 3). Using the previously measured value⁷ of $5.9 \times 10^{13} \text{ cm}^3/\text{mol-s}$ for the HF(3)-D removal rate, we obtain a value of $(2.6 \pm 1) \times 10^{13} \text{ cm}^3/\text{mol-s}$ for the removal rate of DF(v = 4) by D atoms. The values of $9.1 \times 10^{11} \text{ cm}^3/\text{mol-s}$ and $3.4 \times 10^{11} \text{ cm}^3/\text{mol-s}$ for the deactivation rates^{9,10} of HF(v = 3) and DF(v = 4) by D₂ can be neglected.

D. THE REMOVAL RATE OF DF(v = 4) BY H ATOMS

The DF(v = 4) fluorescence decayed exponentially in the gas flows containing H₂ without the microwave discharge. However, with the microwave discharge on and, therefore, H atoms present, the observed fluorescence rose to a maximum at about 30 μs before beginning its exponential decay. A fluorescence trace is shown in Fig. 3. Since DF 4 \rightarrow 0 fluorescence and HF 3 \rightarrow 0 fluorescence fall within the spectral bandpass of our photomultiplier-filter system, a logical interpretation is the following. DF(v = 4) is removed by the three reactions



where M = H₂, DF, etc. The F atoms react with the abundant H₂ to produce HF(v = 3) in the reaction



Only DF(v = 4) emission produces the photomultiplier signal immediately after the laser pumping of DF. However, at longer times both DF(v = 4) and HF(v = 3) fluorescences contribute to the signal. Analytical expressions are derived in the Appendix for the fluorescence intensities of these two species. They indicate that the exponential decay rate at long times can be related to the total removal rate of DF(v = 4) by H atoms. Because of the rapid quenching

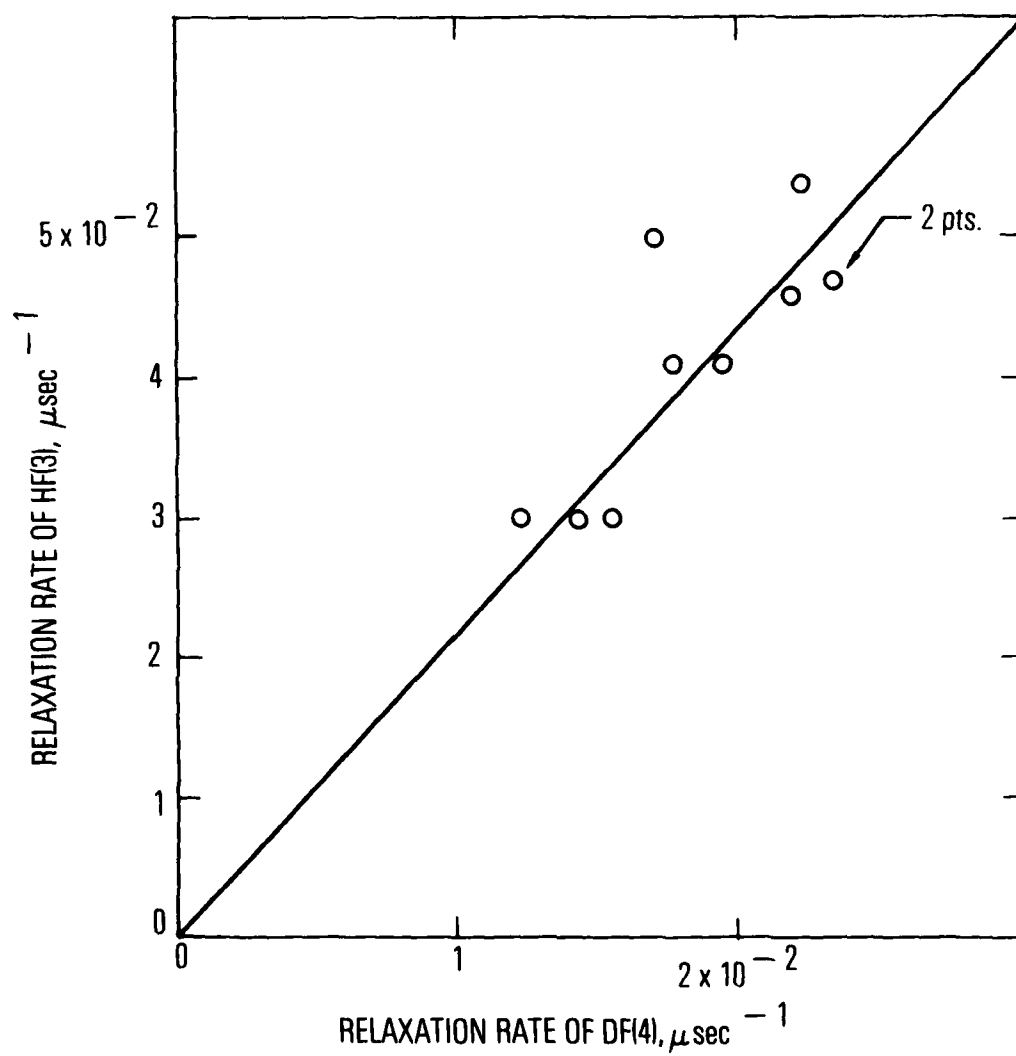


Fig. 2. Rates of HF(v = 3) Removal by D Atoms Versus Rates of DF(v = 4) Removal by D Atoms

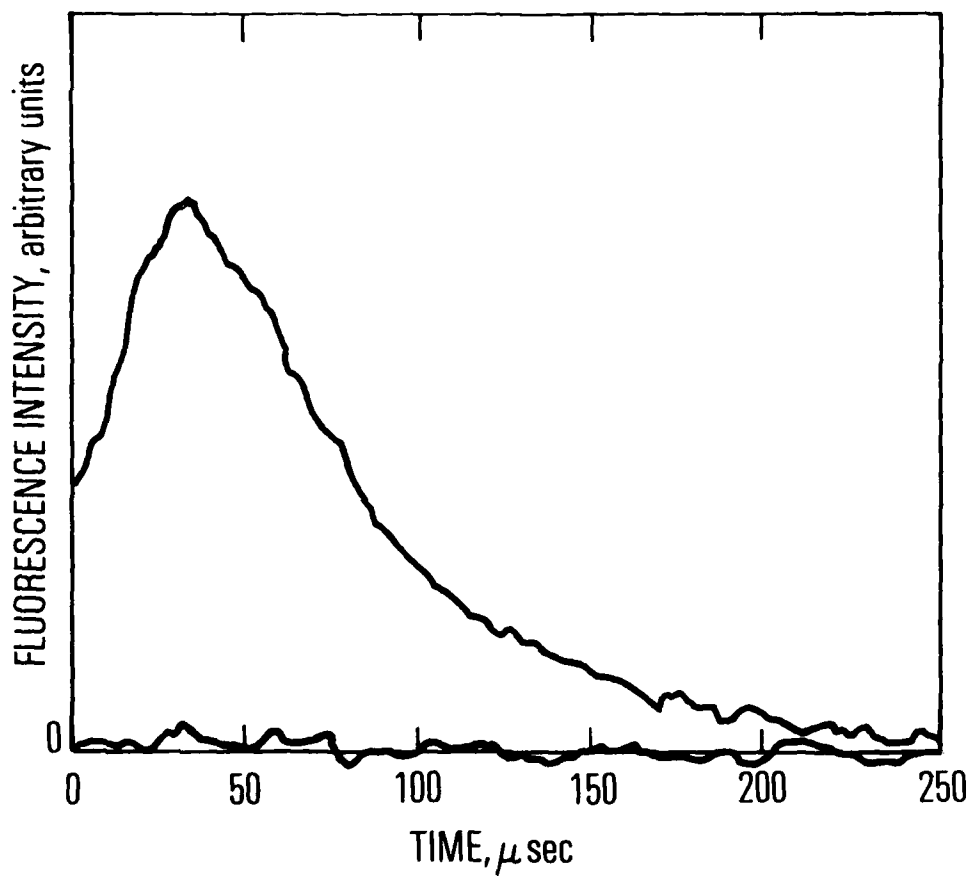


Fig. 3. Fluorescence Signal Obtained with DF Pumped to DF($v = 4$) in the Presence of H Atoms

rate of HF($v = 3$) by H atoms, the HF($v = 3$) fluorescence is essentially proportional to the DF($v = 4$) concentration. The total fluorescence intensity at long times (extrapolated back to time = 0), and the initial DF($v = 4$) fluorescence intensity can be used to estimate the contribution of Reaction (5) to the total removal rate. From the Appendix we have

$$\left(\frac{I_{\text{total}}^0}{I_{\text{DF}}^0}\right) - 1 = \frac{S_{\text{HF}}}{S_{\text{DF}}} \frac{A_{\text{HF}}}{A_{\text{DF}}} F \frac{\tau_1 \tau_2}{\tau_2 - \tau_1} k_5 [\text{H}] \quad (9)$$

where I_{total}^0 is the intensity obtained by extrapolating the total intensity of long times back to time = 0, I_{DF}^0 is the DF intensity at time = 0, S is the relative response of the photomultiplier at the wavelengths of the HF and DF lines, A is the Einstein coefficient for the lines, F is the fraction of HF($v = 3$) produced by Reaction (8), and τ_1 and τ_2 are the rise times and decay times, respectively. A value of 1.24×10^3 was determined for $(S_{\text{HF}}A_{\text{HF}}/S_{\text{DF}}A_{\text{DF}})$ by a detailed calibration of the detector, which folded in the values of A from Ref. 11. This large value means the photomultiplier is 1.24×10^3 more sensitive for HF($v = 3$) detection than for DF($v = 4$). F has a value³ of 0.28. From the fluorescence trace shown in Fig. 3 we estimate $\tau_2 = 55 \pm 3 \mu\text{s}$, $\tau_1 = 20 \pm 2 \mu\text{s}$, $(I_{\text{total}}^0/I_{\text{DF}}^0) = 5$, and $[\text{H}] = 0.8 \times 10^{-9} \text{ mol/cm}^3$ obtained from HF($v = 3$) decay times. Using these values and Equation (9), we obtain $k_5 = 5 \times 10^{11} \text{ cm}^3/\text{mol-s}$. The decay time of 55 μs compares with a decay time of 130 μs obtained without the microwave discharge (and, therefore, without H atoms). From these decay times we calculate a total removal rate of $(1.3 \pm 0.3) \times 10^{13} \text{ cm}^3/\text{mol-s}$ for DF($v = 4$) by H atoms.

To determine the H atom concentration, the HF impurity in the DF was pumped to HF($v = 3$) with the HF pulsed laser. The HF($v = 3$) fluorescence decayed exponentially with a decay time of 21 μs . This decay time is consistent with the value of $\tau_1 = (k[\text{H}])^{-1}$, where k is the rate coefficient for the removal of HF($v = 3$) by H atoms. The decay time of HF($v = 3$) fluorescence in the first experiment is described by the same equation to a good approximation.

IV. DISCUSSION

The present data for $DF(v = 3)$ deactivation by H and D atoms contain large uncertainties because of the relatively small changes in the decay times with and without the microwave discharge. In spite of their large uncertainties (Table 4), they are smaller by a factor of 10 than the rate coefficients for the deactivation of $HF(v = 3)$ by H and D atoms.⁷ The rates of $HF(v)$ and $DF(v)$ deactivation by diatomic molecules have been found to scale as v^n when the deactivation process is exothermic.^{9,10} The scaling parameter is independent of the diatomic collision partner, and for $DF(v)$ deactivation $n = 1.9 \pm 0.1$. It is not known whether the same scaling parameter applies to $DF(v)$ deactivation by atoms, and the present data, given in Table 4, are too imprecise to determine the dependence. It would appear, however, that the rate coefficients for $DF(v = 3)$ deactivation by H and D atoms are faster than we would predict on the basis of the $DF(v = 1)$ data and a $v^{1.9}$ scaling.

The rate coefficients obtained for $DF(v = 4)$ removal by H and D atoms are given in Table 4. They are approximately five times larger than the $DF(v = 3)$ -H, D deactivation rate coefficients, but two to four times smaller than the $HF(v = 3)$ -H, D deactivation rates. The rate coefficient for $DF(v = 4)$ removal by Reaction (3), the reverse of the pumping reaction, can be estimated on the basis of the overall reaction rate for $F + D_2$, the relative vibrational distributions, and the equilibrium constant $K_{3,-3} = k_3/k_{-3}$. Cohen and Bott³ reviewed the data for the $F + D_2$ reaction and recommended a value of $(0.95 \pm .17) \times 10^{13} \text{ cm}^3/\text{mol-s}$ for the rate coefficient at 295 K and recommended the Perry and Polanyi value¹² of 0.26 for the branching fraction into the $v = 4$ level. A value of $K_{3,-3} = 1.03$ can be calculated from the thermodynamic data in Table 5. Using these values we obtain a value of $k_3 = 2.6 \times 10^{12} \text{ cm}^3/\text{mol-s}$, with perhaps a 50% uncertainty. Since this value is almost an order of magnitude smaller than the present measured value of the total removal rate of $DF(v = 4)$ by D atoms, it would appear that vibrational deactivation, Reactions (1) and (2), is the dominant mechanism for $DF(v = 4)$ removal.

Berry studied the reaction¹³

Table 4. Removal Rate Coefficients

Excited Molecule	Rate Coefficients, cm ³ /mol-s			
	H	D	H ₂	D ₂
DF(v = 1)	^a (6.7 ± 1.8) × 10 ¹⁰	^a (0 ± 9) × 10 ¹⁰	^b 1.0 × 10 ¹⁰	^b 3.8 × 10 ¹¹
DF(v = 3)	^c (2 ± 2) × 10 ¹²	^c (5 ± 2) × 10 ¹²	^b 8.2 × 10 ¹⁰	^b 2.8 × 10 ¹¹
DF(v = 4)	^c (1.3 ± 0.6) × 10 ¹³	^c (2.6 ± 1) × 10 ¹³	^b 1.68 × 10 ¹¹	^b 3.4 × 10 ¹¹
DF(v = 4)	^d (5 ± 2) × 10 ¹¹	^e (3 ± 1.5) × 10 ¹²		
^a Ref. 5				
^b Ref. 9				
^c Present results.				
^d Reaction (5), present results.				
^e Reaction (3), see text.				

Table 5. Thermochemical Data^a

Species	S°_{298} cal/mol-K	$\Delta H^{\circ}_{f, 298}$ kcal/mol
F	37.917	18.860
D	29.455	52.992
H	27.392	52.103
D ₂	34.620	0.000
H ₂	31.207	0.000
HD	34.343	0.077
DF(v = 0)	42.924	-65.85
DF(v = 4)	42.924	-34.160

^aSee Ref. 14.



and reported the rate of the $F + DH \rightarrow DF + H$ reaction to be 0.51 ± 0.03 of the rate of the $F + D_2 \rightarrow DF + D$ reaction. He also reported the branching fraction into $DF(4)$ to be 0.13 ± 0.09 . These values, together with the value of $(0.95 \pm 0.17) \times 10^{13} \text{ cm}^3/\text{mol-s}$ for the $F + D_2$ reaction, combine to give $k_{10} = (6.3 \pm 4.0) \times 10^{11} \text{ cm}^3/\text{mol-s}$. A value of $K_{10,-10} = 2.0$ can be calculated from the thermochemical data of Table 5. This results in a value of $(3.1 \pm 2) \times 10^{11} \text{ cm}^3/\text{mol-s}$ for k_{-10} , which is in agreement with the value of $(5 \pm 2) \times 10^{11}$ measured in the present study. This good agreement between the directly measured value of k_{-10} and the value calculated from the value of k_{10} reinforces our confidence in the calculations of the removal rates of $HF(v = 3)$, $DF(v = 4)$ by H and D atoms by the reverse of the pumping reactions.

It has been suggested⁸ that the fast removal rates of $HF(v = 3)$ and $DF(v = 4)$ by H and D atoms might be the result of the back reaction of the pumping reactions. Polanyi and coworkers⁸ used the method of chemiluminescence depletion with mass spectrometry (CDMS) to study removal rates of $HF(v = 1 - 6)$ by D atoms. With this technique they could determine relative depletion rates of the various levels and appearance rates of products. They found the depletion rates of $HF(v)$ to increase dramatically for $v = 3$ through 6 from the very low rates for $v = 1$ and 2. When they added D atoms to a gas mixture containing $HF(1)$, $HF(2)$, and $HF(3)$, they observed the fast removal of $HF(3)$ and the appearance of HD. No $HF(v = 1,2)$ increases were observed. Their results suggest that the removal of $HF(3)$ by D atoms occurs solely by the isotopic analog of Reaction (1). This is inconsistent, however, with the results of the present study in which the rate coefficient of $DF(v = 4)$ removal by D atoms was found to be almost an order of magnitude larger than that estimated above for Reaction (3) (the reverse of the $F + D_2$ pumping reaction). On the basis of the present data we conclude that vibrational deactivation must be the major channel for $DF(v = 4)$ removal by H and D atoms. The dominance of vibrational deactivation was postulated by Heidner

and Bott⁷ for the fast removal rates of HF($v = 3$) by H and D atoms and the T^{-1} temperature dependence of these rate coefficients between 200 and 295 K.

Of concern to laser modelers is the effect of D-atom deactivation on laser performance. In the "cold reaction" chemical laser there is one D atom produced for each DF molecule. According to the recommended rate coefficients given in Ref. 3, the V-R,T deactivation of DF($v = 3$) by DF has a rate coefficient of 4×10^{12} cm³/mol-s at 295 K, and the V-V exchange between DF($v = 3$) and DF($v = 0$) has a rate coefficient of 1×10^{13} cm³/mol-s. Therefore, with the rate coefficient of $5 \pm 2 \times 10^{12}$ cm³/mol-s obtained in the present study, the deactivation of DF($v = 3$) by D atoms is significant but not dominant in determining the removal rate of DF($v = 3$). On the other hand, the deactivation of DF($v = 4$) by atoms may well dominate over the self-deactivation by DF. According to Ref. 3, the recommended rate coefficients for the V-R,T deactivation of DF($v = 4$) by DF and for the V-V exchange between DF($v = 4$) and DF($v = 0$) are 7×10^{12} cm³/mol-s and 7.4×10^{12} cm³/mol-s, respectively. Therefore, the value of $(2.6 \pm 1) \times 10^{13}$ cm³/mol-s obtained in the present study for the deactivation of DF($v = 4$) by D atoms is larger than the sum of the V-V and V-R,T self-deactivation rate coefficients of DF($v = 4$) by DF.

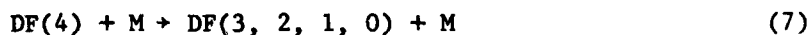
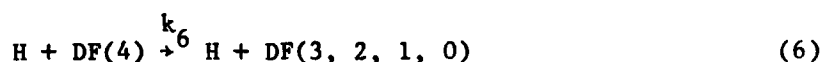
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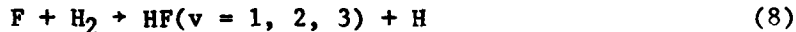
APPENDIX

THE REMOVAL RATE OF $DF(v = 4)$ BY H ATOMS

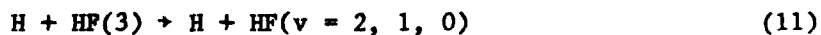
The $DF(v = 4)$, which is produced by the laser pulse, is removed by the three reactions



where $M = H_2, DF$, etc. The F atoms react with the abundant H_2 to produce $HF(v = 3)$ in the reaction



The $HF(3)$ is then deactivated by H atoms by the process



Since the reverse reactions can be neglected when compared to the forward directions of Reactions 5, 6, and 7, the $DF(4)$ disappears exponentially. The population of $DF(4)$ can be described by

$$[DF(4)] = [DF(4)]_0 \exp\left(\frac{-t}{\tau_2}\right) \quad (12)$$

where $[DF(4)]_0$ is the initial DF concentration produced by the laser pulse, and τ_2 is the exponential decay time.

When the F atoms produced by Reaction (5) react quickly to form HF in Reaction (8), the formation rate of $HF(v = 3)$ can be described by the term

$F k_5[H] [DF(4)]$ where F is the fraction of HF produced in the $v = 3$ vibrational level by Reaction (8). The removal rate of HF($v = 3$) is simply $k_{11}[H] [HF(3)]$. The rate equation for the formation and removal of HF(3) can be solved to obtain

$$[HF(3)] = F k_5[H] [DF(4)]_0 \frac{\tau_1 \tau_2}{\tau_2 - \tau_1} \left\{ \exp\left(\frac{-t}{\tau_2}\right) - \exp\left(\frac{-t}{\tau_1}\right) \right\} \quad (13)$$

where τ_1 is the rise time defined by $1/\tau_1 = k_{11}[H]$. The intensity of the HF(3) fluorescence, I_{HF} (actually the photomultiplier signal), is given by

$$I_{HF} = S_{HF} A_{HF} [HF(v = 3)] \quad (14)$$

where S_{HF} is the response of the photomultiplier at the wavelengths of the HF lines, and A_{HF} is the Einstein coefficient for the lines. A similar equation holds for I_{DF} .

I_{total}^0 , the total intensity of $I_{DF} + I_{HF}$ extrapolated back to time = 0 from its values at long times, and I_{DF}^0 , the DF fluorescence intensity at time = 0, can be related to k_5 by the equation

$$\left(\frac{I_{total}^0}{I_{DF}^0} \right) - 1 = \frac{S_{HF}}{S_{DF}} \frac{A_{HF}}{A_{DF}} F \frac{\tau_1 \tau_2}{\tau_2 - \tau_1} k_5[H] \quad (9)$$

Therefore, the value of k_5 can be determined from the fluorescence intensity profile if $[H]$, the density of H atoms, is known. The values of A and F are available, and the relative responses, S_{HF} and S_{DF} , can be determined by a calibration.

LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military space systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

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Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiation transport in rocket plumes, applied laser spectroscopy, laser chemistry, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and bioenvironmental research and monitoring.

Electronics Research Laboratory: Microelectronics, GaAs low-noise and power devices, semiconductor lasers, electromagnetic and optical propagation phenomena, quantum electronics, laser communications, lidar, and electro-optics; communication sciences, applied electronics, semiconductor crystal and device physics, radiometric imaging; millimeter-wave and microwave technology.

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Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the upper atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, infrared astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.